Journal of Athletic Training 2021;56(6):548–554
doi: 10.4085/40-20

www.natajournals.org

Predictive Ability of Body Fat Percentage and Thigh Anthropometrics on Tissue Cooling During Cold-Water Immersion

Nicholas Rech, DPT*; Eadric Bressel, EdD†; Talin Louder, PhD†

*Rech Physio, Grand Island, NE; †Utah State University, Logan

Context: Cold-water immersion (CWI) is a common aid in exercise recovery. The effectiveness of CWI depends on the magnitude of muscle and core cooling. Individual cooling responses to CWI vary and are likely influenced by the CWI dose and individual physiological characteristics.

Objective: To evaluate body fat percentage and thigh anthropometric values as predictors of intramuscular and skin-cooling responses to CWI.

Design: Descriptive laboratory study.

Setting: Sports medicine research center.

Patients or Other Participants: Sixteen young adults (8 males, 8 females, age = 24.3 ± 1.84 years, height = 176.4 ± 12.7 cm, mass = 86.6 ± 29.4 kg).

Intervention(s): Body fat percentage was measured using a 3-site skinfold assessment. Thigh length, thigh circumference, anterior thigh adipose thickness, anterior thigh muscle thickness, and thigh volume were estimated using manual and ultrasound methods. Using sterile techniques, we placed thermocouple probes in the belly of the rectus femoris (2-cm deep to the subadipose tissue) and on the anterior midthigh surface. Participants cycled on an ergometer for 30 minutes at a target heart rate of 130 to 150 beats/min. Postexercise, participants were placed in CWI (immersion depth to the iliac crest; 10°C) until intramuscular temperature was 7°C below pre-exercise baseline temperature, with a maximum immersion duration of 30 minutes.

Main Outcome Measure(s): Intramuscular rectus femoris and thigh skin temperatures measured postexercise, after 10 and 15 minutes of CWI, and post-CWI.

Results: Body fat percentage significantly predicted the rectus femoris cooling magnitude and rate after 10 minutes of CWI, 15 minutes of CWI, and post-CWI ($P < .001$; R^2 range = 0.58–0.67). Thigh anthropometric values significantly predicted the thigh skin-cooling rate post-CWI ($P = .049$; $R^2 = 0.46$).

Conclusions: A simple 3-site skinfold assessment may improve the effective prescription of CWI by allowing estimation of the dose required for minimal muscle tissue cooling.

Key Words: exercise, recovery, hydrotherapy

Key Points

- A 3-site skinfold assessment predicted the intramuscular rectus femoris cooling response to cold-water immersion (CWI) in young adults and may be used to improve the individual specificity of CWI protocols.
- Thigh anthropometric values, in addition to ultrasound-derived muscle and adipose tissue thickness, predicted the thigh skin-cooling response to CWI in young adults but did not improve prediction of the intramuscular rectus femoris cooling response.

Cold-water immersion (CWI) is a widely used treatment modality in exercise stress recovery. Physiological stress from exercise can compromise performance acutely through central and peripheral fatigue as well as exercise-induced muscle damage. Researchers[1–3] suggested that CWI attenuated postexercise stress, thereby improving performance in subsequent bouts of exercise. Furthermore, investigators[4] indicated that improved recovery after CWI occurred via physiological mechanisms that affected central nervous system fatigue, cardiovascular strain, parasympathetic activity, metabolite efflux, edema, and inflammation. Reduced core temperature after CWI was proposed to mitigate central nervous system fatigue by lowering thermal demand.[4] A combination of hydrostatic pressure and increased vasoconstriction during CWI increased central blood flow, stroke volume, and cardiac output, thus increasing parasympathetic activity and reducing cardiovascular strain.[4] Hydrostatic pressure was thought to act by increasing hemodilution and decreasing edema, improving muscle oxygen delivery and metabolite efflux.[4] Lastly, reduced muscle temperature slowed local metabolism, thereby reducing the inflammatory response of skeletal muscle to a strenuous exercise bout.[4]

Responses to CWI are variable and influenced by the CWI protocol, mode of exercise, and individual physiological characteristics.[5] These factors may have played roles in the inconsistent results[2,6–10] regarding the benefits of CWI on recovery from various types of exercise stress. The general consensus is that CWI is effective, with the greatest recovery benefit observed in subsequent bouts of endurance exercise and movements that evoke a stretch-shortening response in muscle.[5]

Cold-water immersion protocols are primarily influenced by 3 components: water temperature, immersion duration, and skin surface area contact with the water. In a review, Stephens et al[5] recommended an optimal water temperature between 10°C and 15°C. However, at these temperatures, the magnitude of muscle cooling was 140% greater with immersion for 20 minutes versus 5 minutes.[5] Moreover, in a meta-analysis of 13 investigations (157 participants), researchers[11] revealed a coefficient of variation of 52% in the core temperature cooling response to CWI. Variability in CWI protocols is important to address because the dose response of CWI on postexercise recovery depends at least partially on the magnitude of skin, muscle, and core cooling. For instance, small magnitudes of cooling may not achieve a dose response, whereas large magnitudes of cooling may acutely impair neuromuscular function.[11]

Vromans et al[12] suggested that a full-body CWI dose of 1.1 (Equation 1), corresponding with 11 minutes of immersion at 10°C, was required to achieve a minimal intramuscular-cooling response of 5°C from the postexercise temperature. This recommendation was based on a collection of data from 26 unique CWI protocols. After correcting for skin area contact with water, Vromans et al[12] observed a significant linear relationship between the CWI dose and intramuscular-cooling response postexercise. Although the linear relationship was statistically significant, their model contained 33% unexplained variance. Thus, even with a standard CWI protocol, the intramuscular-cooling response varies and may be affected by individual physiological characteristics.

$$\text{CWI Dose } \left(\text{Vromans et al}^{12}\right) = \text{CWI Duration} * \left(\frac{1}{\text{Water Temperature}}\right) \quad (1)$$

Body composition and anthropometric values have been suggested as affecting individual variability in the intramuscular-cooling response to CWI.[5] For instance, body surface area, body mass, and the body surface area-to-body mass ratio are thought to influence thermal regulation in humans.[13] Thermal convection and conduction increase with greater body surface area, and greater body mass tends to increase heat production and storage.[14] Thus, a greater body surface area-to-body mass ratio is believed to facilitate heat loss, with a lesser ratio facilitating heat storage.[15] Moreover, greater body surface area-to-body mass ratios implicate body density as a factor in the thermal responses to CWI.

It is implicit that greater percentages of body fat mass reduce total body density in humans. Body fat may be an important variable in the effectiveness of CWI given its low level of heat conductivity.[16] Moreover, a reduction in body density due to a greater proportion of body fat effectively reduces blood volume per unit of body weight, which is thought to affect conductive tissue heat transfer.[14] An evaluation of the associations among body composition, anthropometric values, and variable tissue-cooling responses to CWI is needed. Recently, Stephens et al[11] observed a significant negative correlation ($r = \sim 0.50–0.60$) between body fat percentage and the core cooling response to full-body CWI (15 minutes at 15.9°C). To the best of our knowledge, no researchers have explored the influence of body composition and local anthropometric values on the intramuscular and skin-cooling response to CWI. Thus, the purpose of our investigation was to evaluate the influence of body fat percentage and thigh anthropometric values on the rectus femoris and anterior thigh skin-cooling responses to a standard CWI protocol. We hypothesized that body fat percentage and thigh anthropometric values would predict the intramuscular and skin-cooling responses.

METHODS

Participants

Sixteen participants (age = 24.3 ± 1.84 years, height = 176.4 ± 12.7 cm, mass = 86.6 ± 29.4 kg) were recruited from the university community. Participants met the inclusion criteria if they self-reported that they had no lower extremity injury that would prevent pedaling on a stationary ergometer for 30 minutes at moderate-to-hard intensity, had no physiological condition that would affect normal tissue thermodynamics, and were willing to undergo a maximum of 30 minutes of CWI. They self-reported physical activity levels ranging from 1 to 2 days of light-intensity exercise per week to 5 to 6 days of moderate- to high-intensity exercise per week. Participants were recruited on a volunteer basis and were required to provide consent via signature on an informed consent document approved by the university institutional review board, which also approved the study.

Procedures

Recruits were familiarized with all procedures before testing. They reported to a single data-collection session located at the university Sports Medicine Research Center and refrained from consuming alcohol, caffeine, or food for 1 hour and from any vigorous activities for 2 hours before the test to help stabilize peripheral hemodynamic values. After arrival, participants were evaluated for the following anthropometric variables: body fat percentage, thigh length, thigh circumference, anterior thigh adipose thickness, anterior thigh muscle thickness, and thigh volume.

Body fat percentage was estimated using the Jackson and Pollock 3-site skinfold measurement.[17] The Jackson and Pollock method is commonly used by researchers, is feasible to complete as a field assessment, and accurately predicts body composition when compared with hydrostatic weighing ($r = 0.92$).[18] Thigh length was estimated as a manual measurement of the distance between the greater trochanter and 1 cm above the base of the patella. Thigh circumference was estimated as the circumference at the midpoint of the thigh length. The location for the thigh circumference measurement was selected with reference to Tothill and Stewart,[19] who demonstrated that using a midthigh circumference measurement to estimate thigh volume was highly accurate when compared with magnetic resonance imaging. With each individual standing, we estimated anterior thigh adipose and muscle thickness via ultrasound (BodyMetrix A-Mode Ultrasound; IntelaMetrix). Anterior thigh adipose and muscle thickness were estimated based on the scanning depth of the adipose-muscle and muscle-bone interfaces. After the ultrasound scan, conductive gel was removed with a paper towel. Using thigh length (h), thigh circumference (C_T), and anterior thigh adipose thickness (T) as input variables, we estimated thigh volume using a series of equations (Equations 2–8), assuming that the thigh segment was effectively modeled as a truncated cone.[19]

$$\text{Cross-Sectional Area (CSA)} = \frac{C_T^2}{4\pi} \quad (2)$$

$$\text{Circumference of Lean Tissue } (C_L) = C_T - (\pi * T) \quad (3)$$

$$\text{Lean Tissue Cross-Sectional Area } (A_L) = \frac{(C_L - (2\pi * T))^2}{4\pi} \quad (4)$$

$$\text{Adipose Tissue Cross-Sectional Area } (A_F) = (C_T * T) - (\pi * T^2) \quad (5)$$

$$\text{Lean Thigh Volume } (V_L) = A_L * h \quad (6)$$

$$\text{Adipose Thigh Volume } (V_F) = A_F * h \quad (7)$$

$$\text{Thigh Volume } (V_T) = V_L + V_F \quad (8)$$

After collecting the anthropometric data, we placed a mark on the anterior thigh, at approximately the length midpoint, for each person. This mark indicated the location of temperature probe insertion. Thereafter, a 100-cm^2 area surrounding the insertion location was cleaned with povidone-iodine swabs. We applied 3 swabs to each participant using a circular pattern. We then applied a local anesthetic (bupivacaine 0.5%; Hospira, Inc) 1 cm superior to the mark on the thigh.

After preparing the skin, we inserted a catheter (18 gauge, 8.89 cm; PSS World Medical) into the rectus femoris 1 cm superior to the marked thigh location. A sheath of tubing surrounding the catheter was cut to a length that permitted the needle to reach a depth of 2 cm in the subadipose tissue of all participants. After the catheter was approximated to the standard depth, we fed an IT-18 implantable thermocouple (Physitemp Instruments, LLC) through the catheter. To ensure that the thermocouple remained at the appropriate depth, pressure was maintained on the thermocouple wire as the catheter was removed from the thigh. After removing the catheter, we taped the thermocouple wire to the thigh using Cover-Roll dressing (BSN Medical).

A surface thermocouple was affixed to the anterior thigh 1 cm inferior to the marked location. The surface thermocouple was waterproofed via application of an 8-cm by 8-cm strip of transparent waterproof adhesive film (OPSITE; Smith & Nephew). The outer borders of the adhesive film were anchored using strips of adhesive stretch tape (Cover-Roll Stretch; BSN Medical). We then affixed the surface thermocouple leads to a location just superior to the iliac crest using strips of adhesive stretch tape. Leads were affixed to the hip to prevent them from being disturbed during the exercise protocol, with sufficient slack to permit unobstructed movement of the thigh. We then connected both thermocouples to an 8-channel Thermes data-acquisition device (accuracy of ±0.1°C, 0.2%; Physitemp Instruments, LLC) set to record intramuscular and skin temperature at a sample rate of 2 Hz.

Pre-exercise baseline intramuscular and skin temperatures were recorded while participants sat dormant on a stationary cycle ergometer (Freemotion Fitness). They then cycled on the ergometer for 30 minutes, during which heart rate was monitored continuously using a pulse oximeter (Nellcor Puritan Bennett, Inc). At the onset of exercise, heart rate increased from resting to a range of 130 to 150 beats/min, which was then maintained through the exercise. We selected this target heart rate range because it represents an age-specific moderate to hard intensity during the exercise bout.[20] Immediately after the exercise, participants stood in a temperature-regulated cold plunge pool (Classic; HydroWorx) up to the level of the iliac crest. The CWI temperature was maintained at 10°C, which is within the midrange of CWI temperatures used by previous researchers.[12]

During CWI, temperature recordings were monitored until both intramuscular and skin temperatures fell to 7°C below the pre-exercise baseline, at which point participants were removed from the CWI protocol. The rationale for using a criterion of 7°C below pre-exercise baseline was based on earlier authors'[21] suggestion that tissue metabolism was halved when tissue was cooled by 7°C to 10°C. However, some individuals did not cool to the 7°C criterion. In this case, they continued CWI for 30 minutes, at which point they were removed from the CWI protocol. We selected 30 minutes as the cutoff duration because it is uncommon for athletes to remain in CWI for longer than this amount of time.

After the CWI protocol, participants dried off and stood in a temperature-controlled environment (21.7°C). Once the intramuscular temperature began to warm, temperatures were recorded for a period of 15 minutes. After the rewarming period, we withdrew the intramuscular and surface thermocouples. Insertion depth of the intramuscular thermocouple was confirmed to have remained at the selected depth before removal, and visual inspection revealed no deformation of the thermocouple leads due to muscle contraction. After removal of the thermocouples, the thigh insertion site was cleansed using an alcohol wipe and bandaged. All invasive procedures were conducted while adhering to sterile practices.

Data Analysis

Independent variables in this investigation were body fat percentage, thigh length, thigh circumference, anterior thigh adipose thickness, anterior thigh muscle thickness, and thigh volume. Dependent measures were estimated from the temperature data acquired via the intramuscular and surface thermocouples. Intramuscular temperatures postexercise, after 10 minutes of CWI, after 15 minutes of CWI, and post-CWI were used to determine the dependent measures. We estimated the intramuscular-cooling magnitude by taking the temperature difference at each time point with respect to postexercise temperature (Equation 9). Intramuscular-cooling rates after 10 minutes of CWI, 15 minutes of CWI, and post-CWI were estimated by calculating the ratio of cooling magnitude to duration of time in CWI (Equation 10). Skin temperatures postexercise and post-CWI were used to compute dependent measures. Skin-cooling magnitude (Equation 9) and rate (Equation 10) post-CWI were included as dependent measures.

$$\text{CWI Cooling Magnitude} = \text{CWI Temp} - \text{Postexercise Temperature} \quad (9)$$

$$\text{CWI Cooling Rate} = \frac{\text{CWI Cooling Magnitude}}{\text{Time Duration of CWI}} \quad (10)$$

Table 1. Central Tendency and Dispersion Results for Body Fat Percentage and Thigh Anthropometric Values[a]

Measurement	Mean ± SD
Body fat, %	21.7 ± 7.6
Thigh length, cm	40.1 ± 4.0
Muscle thickness, cm	3.9 ± 0.8
Thigh volume, cm	9576.2 ± 2589.4
Thigh circumference, cm	57.1 ± 5.6
Adipose thickness, cm	1.1 ± 0.4

[a] Data are from a sample of 16 young adult males and females. Participants performed 30 minutes of exercise on a cycle ergometer while maintaining a heart rate between 130 and 150 beats/min. After the exercise bout, participants were placed in waist-level cold-water immersion until the intramuscular temperature of the rectus femoris decreased by 7°C from the pre-exercise baseline temperature or for a maximal duration of 30 minutes.

Table 2. Results of Simple Linear Regression Performed Between Body Fat Percentage and the Intramuscular-Cooling Response to a Standardized CWI Protocol[a]

Response Variable	Intercept	Body Fat, %	F Value	R^2 Value	P Value
Intramuscular temperature, °C					
10-min Post-CWI	7.8	−0.24	24.85	0.66	<.001
15-min Post-CWI	11.3	−0.32	26.40	0.67	<.001
End of CWI	13.7	−0.30	18.23	0.58	<.001
Intramuscular-cooling rate, °C × min^{-1}					
10-min Post-CWI	−0.8	0.02	24.85	0.63	<.001
15-min Post-CWI	−0.8	0.02	26.38	0.64	<.001
End of CWI	−0.7	0.02	22.28	0.60	<.001

Abbreviation: CWI, cold-water immersion.

[a] Intramuscular rectus femoris temperature was recorded at mid-thigh in 2 cm of subadipose tissue. Data are from a sample of 16 young adult males and females. Participants performed 30 minutes of exercise on a cycle ergometer while maintaining a heart rate between 130 and 150 beats/min. After the exercise bout, participants were placed in waist-level CWI until the intramuscular temperature of the rectus femoris decreased by 7°C from the pre-exercise baseline temperature or for a maximal duration of 30 minutes. The intramuscular-cooling response was evaluated by estimating the intramuscular-cooling magnitude (Δ °C) and rate (Δ °C × min^{-1}) after 10 minutes of CWI, after 15 minutes of CWI, and at the end of the CWI protocol with respect to the postexercise intramuscular temperature.

Statistical Analysis

Statistical analyses were performed in RStudio (version 1.1.456). Using stepwise regression, we explored the association of body fat percentage and thigh anthropometric values on the intramuscular and skin-cooling magnitude and rate. Stepwise regression returned linear models for each dependent measure based on the sequential replacement of predictor variables. The sequential replacement of predictor variables led to the selection of optimized linear models for each dependent measure iteratively by minimizing the Akaike information criterion.[22] Optimized linear models were then evaluated using linear regression. We set the level of statistical significance at a P value of .05.

RESULTS

All participants completed testing as planned, and a post hoc power analysis (version 3.1.9.4; G*Power; Franz Faul, Universitat Kiel) of the intramuscular-cooling regressions revealed that this investigation was sufficiently powered (power [1 − β] = 0.985–0.999). The central tendency and dispersion results for body fat percentage and thigh anthropometric values are presented in Table 1.

For all dependent measures relating to intramuscular cooling, stepwise regression returned a simple linear model with body fat percentage as the sole predictor variable. Linear relationships between body fat percentage and intramuscular cooling were significant (F range = 18.2–26.4; R^2 range = 0.58–0.67; $P < .001$; Table 2).

For skin-cooling magnitude post-CWI, stepwise regression returned a multiple linear model with thigh circumference, thigh volume, and body fat percentage as predictor variables. For skin-cooling rate post-CWI, stepwise regression returned a multiple linear model with anterior thigh adipose thickness, anterior thigh muscle thickness, thigh length, thigh circumference, and thigh volume as predictor variables. The multiple linear model of the skin-cooling rate post-CWI was significant ($F = 3.5$; $R^2 = 0.46$; $P = .049$; Table 3). The multiple linear model of the skin-cooling magnitude post-CWI did not reach statistical significance ($F = 2.3$; $R^2 = 0.38$; $P = .135$; Table 3).

DISCUSSION

The purpose of our investigation was to evaluate whether body fat percentage and thigh anthropometric values could predict rectus femoris and thigh skin-cooling responses to a standardized CWI protocol. Pre-exercise baseline intramuscular temperature was 35.2 ± 1.1°C. Postexercise intramuscular temperature (37.5 ± 0.6°C) was within the range of temperatures (35.6–39.5°C) reported by earlier researchers.[12] The coefficient of variation for postexercise intramuscular temperature was low (1.7%) and likely explained by tightly controlled central thermoregulation during exercise and the performance of a standardized exercise bout. During CWI, the coefficients of variation for intramuscular-cooling magnitude (7.0%–10.9%) and rate (60.4%–86.9%) increased substantially, which is consistent with the variable responses to CWI demonstrated by previous investigators.[11,12] Post-CWI intramuscular temperature in our sample was 30.3 ± 3.3°C.

A main finding was that body fat percentage, estimated from a 3-site skinfold assessment, was a significant predictor of intramuscular-cooling response to CWI. Specifically, body fat percentage predicted the intramuscular-cooling magnitude and rate with shared variances ranging between 58% and 67%. It is not surprising that body fat percentage explained more than half of the variance in intramuscular-cooling response to CWI. Our findings confirm that body fat exhibited strong insulative thermal properties that slowed muscle tissue cooling during a standardized CWI protocol.

Thigh anthropometric values were considered for inclusion as predictors of intramuscular-cooling response to CWI. However, stepwise regression returned optimized linear models with body fat percentage as a single predictor. Thus, thigh anthropometric values did not improve prediction of the intramuscular-cooling response, which contrasted with our hypothesis. The coefficients of variation for participant thigh length (10%), muscle thickness (21%), thigh volume (27%), and thigh circumference (10%) were lower than for body fat percentage

Table 3. Results of Multiple Linear Regression Evaluating the Association of Body Fat Percentage and Thigh Anthropometric Values on the Skin-Cooling Response to a Standardized CWI Protocol[a]

Response Variable	Intercept	Thigh Volume, cm^3	Thigh Circumference, cm	Body Fat, %	Thigh Length, cm	Muscle Thickness, cm	Adipose Thickness, cm	F Value	R^2 Value	P Value
Skin temperature post–CWI, °C	3.15	−0.001	0.58	−0.21				2.29	0.38	.14
CWI skin-cooling rate, °C × min^{-1}	7.63	0.0005	−0.14		−0.12	−0.20	0.64	3.53	0.46	.049

Abbreviation: CWI, cold-water immersion.

[a] Skin temperature was recorded on the surface of the anterior midthigh. Data are from a sample of 16 young adult males and females. Participants performed 30 minutes of exercise on a cycle ergometer, while maintaining a heart rate between 130 and 150 beats/min. After the exercise bout, participants were placed in waist-level CWI until the intramuscular temperature of the rectus femoris decreased by 7°C from the pre-exercise baseline temperature or for a maximal duration of 30 minutes. The skin-cooling response was evaluated by estimating the skin-cooling magnitude (Δ °C) and rate (Δ °C*min^{-1}) at the end of the CWI protocol with respect to the postexercise skin temperature.

(35%) and adipose thickness (36%). In addition, these values were lower than earlier observations[23] of thigh skinfold thickness in National Collegiate Athletic Association Division I athletes (41%) and recreationally active collegiate students (46%). It is possible that the reduced variability in thigh anthropometric values limited their power to predict the intramuscular-cooling response compared with body fat percentage.

Unexplained variance in our optimized intramuscular-cooling models ranged between 33% and 42%. Age, sex, and ethnicity may also introduce variability into CWI cooling responses[5]; yet the influence of these factors was suggested as resulting from a close relationship with body composition.[5] Thus, a rationale for the unexplained variance between body fat percentage and the intramuscular-cooling response to CWI may be linked to physiological differences unrelated to body composition.

Cardiovascular dynamics, aerobic capacity, anaerobic capacity, and energy support from metabolic pathways are physiological variables that may influence the intramuscular-cooling response to CWI. For instance, Del Rosso et al[24] noted that heart rate was slower to return to resting levels after an exercise bout that relied predominantly on anaerobic versus aerobic metabolism. Our exercise bout was standardized to heart rate, but it may be that participants' cycling performance was supported by varied levels of anaerobic and aerobic metabolic contributions to the overall energy expenditure. In addition, participants varied substantially in their self-reported weekly exercise. This is important when considering that larger blood volumes and improved cardiovascular dynamics are associated with the aerobic fitness level[25,26] and likely enhance conductive tissue heat transfer.[14] For instance, blood volume was significantly correlated with peak oxygen consumption ($\dot{V}O_{2peak}$; $r = 0.762$). Future researchers should consider examining variables related to anaerobic and aerobic fitness, which may improve prediction of the intramuscular-cooling response to CWI beyond our results.

For practicality, we assessed body fat percentage by taking skinfold measurements at 3 anatomical sites, which were input into regression equations developed by Jackson and Pollock.[17] This approach has acceptable accuracy and reliability compared with ultrasound imaging and laboratory reference methods.[18,27–30] Ultrasound imaging is among the most practical laboratory methods of body composition assessment.[31] We estimated adipose thickness using A-mode ultrasound; however, the optimal linear models selected from stepwise regression suggested that skinfold assessments were more predictive of the intramuscular-cooling response. Thus, local thigh adipose tissue thickness, derived from ultrasound, did not improve the strength of our models. Skinfold and ultrasound imaging measurements of subcutaneous thigh adipose tissue were reliable and highly correlated ($r = 0.698$–0.943) when performed by skilled technicians.[32] Moreover, skinfolds perform as well or better than ultrasound imaging compared with hydrodensitometry,[28,30] computed tomography,[29] and dual-energy X-ray absorptiometry.[27] Although the accuracy and reliability of skinfolds are acceptable for field-based assessment, measurement error may have contributed meaningfully to the unexplained variance in our intramuscular-cooling models.

Pre-exercise skin baseline temperature was 31.1 ± 1.0°C. Postexercise and post-CWI skin temperatures were 32.7 ± 1.6°C and 11.3 ± 1.6°C, respectively. Stepwise regression returned an optimized multiple linear model with thigh anthropometric values as significant predictors of the skin-cooling rate. Specifically, thigh anthropometric values predicted the skin-cooling rate with a shared variance of 46%. Stepwise regression returned an optimized multiple linear model with body fat percentage, thigh volume, and thigh circumference as predictors of skin-cooling magnitude. However, this regression model did not achieve statistical significance.

Because thermoregulation during CWI is related to body surface area and body fat percentage,[33] we expected to observe strong predictive models for the skin-cooling response. Conversely, thigh anthropometric values were marginally predictive of the skin-cooling rate. Our models may have been limited by the sample of 16 participants, yet they also likely reflected the complexity of thermoregulation in humans. Heat dissipation during CWI is achieved through an integrated response to internal and peripheral thermoreception that is influenced strongly by physiological characteristics unrelated to anthropometric values and body composition. For example, fitness level (eg, aerobic capacity and substrate utilization) influenced the core temperature, skin blood flow, cardiovascular dynamics, and sweating response during and postexercise.[33] Thus, similar to our recommendations on intramuscular cooling, predictive models of the skin-cooling response to CWI may be strengthened by including physiological variables of physical fitness. Also notable is that participants were immersed in cold water up to the iliac crest, which left a majority of the skin surface area unexposed. This may have

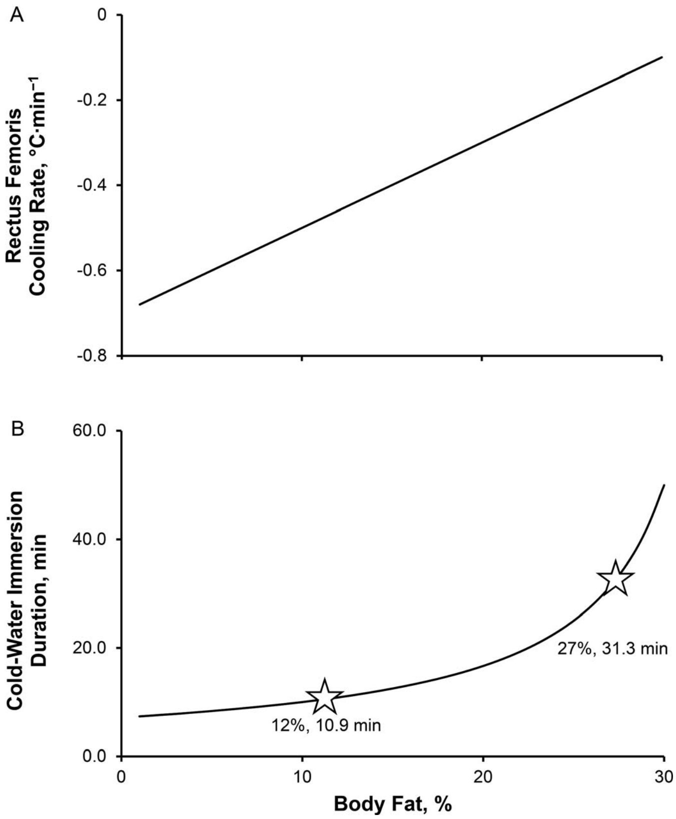

Figure. A, Regression line from linear regression performed between body fat percentage and intramuscular-cooling rate (°C*min^{-1}). Intramuscular rectus femoris temperature was recorded at midthigh in 2 cm of subadipose tissue. The regression was performed using data from 16 young adult males and females. Participants performed 30 minutes of exercise on a cycle ergometer while maintaining a heart rate between 130 and 150 beats/min. After the exercise bout, participants were placed in waist-level cold-water immersion (CWI) until the intramuscular temperature of the rectus femoris decreased by 7°C from the pre-exercise baseline temperature or for a maximal duration of 30 minutes. The intramuscular-cooling rate was evaluated at the end of the CWI protocol with respect to the postexercise intramuscular temperature. B, Estimated relationship between body fat percentage and 10°C CWI duration required to cool the rectus femoris by 5°C from the postexercise temperature. The CWI duration was estimated from the regression line in A.

affected the variability in the thermoregulatory responses across participants.

Our study had limitations. Cutaneous vasoactivity is a primary thermoregulatory mechanism that alters the resistance of heat flux through the skin in response to metabolic heat production and environmental characteristics.[34] To position the intramuscular thermocouple, we injected participants with 0.5% bupivacaine. Such injections cause acute cutaneous vasodilation in humans that last approximately 40 minutes.[34] Our participants were injected with bupivacaine at least 40 minutes before the CWI protocol. Thus, the vasoactive properties of bupivacaine likely affected local skin blood flow during the cycling exercise but had minimal influence on skin temperature during the CWI protocol.

Recommendations for optimizing postexercise CWI protocols have yet to be established. To achieve a meaningful recovery benefit, researchers have suggested that individuals be fully immersed in 10° to 15°C water for at least 10 minutes. The use of body fat percentage to individualize postexercise CWI protocols appears to have value and may improve the likelihood of achieving minimal muscle cooling postexercise. Prior authors[12] advised that muscle tissue be cooled by a minimum of 5°C from the postexercise temperature to activate recovery mechanisms. According to a linear model generated by Vromans et al,[12] an individual would need approximately 11 minutes of CWI at 10°C to achieve 5°C of intramuscular cooling from the postexercise temperature. Our linear model for the intramuscular-cooling rate indicated that 11 minutes of CWI at 10°C was sufficient to cool the rectus femoris by approximately 5°C from the postexercise temperature in individuals with body fat percentages of 12% or less (Figure).

From the clinical and practical perspectives, our findings contribute to a more efficacious prescription of CWI. For instance, applying CWI at the recommended doses to achieve intramuscular cooling and postexercise recovery may not be sufficient in individuals with greater body fat percentages. In practice, it is uncommon for CWI to be applied for durations exceeding 30 minutes. However, our results suggest that 30 minutes of 10°C CWI can only be expected to cool the rectus femoris by the recommended 5°C from postexercise temperature in individuals with body fat percentages below 27% (Figure). Cold-water immersion can be life threatening for those immersed in 10°C water for approximately 10 hours,[35] but in the context of athletic recovery, little is known regarding how long an athlete can be immersed in cold water before it becomes dangerous. Most researchers[12] who studied CWI used immersion durations between 10 and 20 minutes. These durations may be insufficient for athletes with greater body fat percentages. Such insufficiency could be critical because the effectiveness of CWI for reducing postexercise stress and improving performance in subsequent bouts of exercise is at least partially dependent on intramuscular cooling. This may provide an explanation for the inconsistent results on the efficacy of postexercise CWI, and future investigators must consider body composition and physiological variables that may influence individual responsiveness to CWI.

REFERENCES

1. Bleakley C, McDonough S, Gardner E, Baxter GD, Hopkins JT, Davison GW. Cold-water immersion (cryotherapy) for preventing and treating muscle soreness after exercise. *Cochrane Database Syst Rev*. 2012;2012(2):CD008262.
2. Ingram J, Dawson B, Goodman C, Wallman K, Beilby J. Effect of water immersion methods on post-exercise recovery from simulated team sport exercise. *J Sci Med Sport*. 2009;12(3):417–421.
3. Leeder J, Gissane C, van Someren K, Gregson W, Howatson G. Cold water immersion and recovery from strenuous exercise: a meta-analysis. *Br J Sports Med*. 2012;46(4):233–240.
4. Ihsan M, Watson G, Abbiss CR. What are the physiological mechanisms for post-exercise cold water immersion in the recovery from prolonged endurance and intermittent exercise? *Sports Med*. 2016;46(8):1095–1109.
5. Stephens JM, Halson S, Miller J, Slater GJ, Askew CD. Cold-water immersion for athletic recovery: one size does not fit all. *Int J Sports Physiol Perform*. 2017;12(1):2–9.
6. Cochrane DJ. Alternating hot and cold immersion for athlete recovery: a review. *Phys Ther Sport*. 2004;5(1):26–32.

7. Goodall S, Howatson G. The effects of multiple cold water immersions on indices of muscle damage. *J Sport Sci Med*. 2008;7(2):235–241.
8. Jakeman JR, Macrae R, Easton R. A single 10-min bout of cold-water immersion therapy after strenuous plyometric exercise has no beneficial effect on recovery from the symptoms of exercise-induced muscle damage. *Ergonomics*. 2009;52(4):456–460.
9. Rupp KA, Selkow NM, Parente WR, Ingersoll CD, Weltman AL, Saliba SA. The effects of cold water immersion on 48-hour performance testing in collegiate soccer players. *J Strength Cond Res*. 2012;26(8):2043–2050.
10. Wilcock IM, Cronin JB, Hing WA. Physiological response to water immersion: a method for sport recovery? *Sports Med*. 2006;36(9):747–765.
11. Stephens JM, Sharpe K, Gore C, et al. Core temperature responses to cold-water immersion recovery: a pooled-data analysis. *Int J Sports Physiol Perform*. 2018;13(7):917–925.
12. Vromans BA, Thorpe RT, Viroux PJ, Tiemessen IJ. Cold water immersion settings for reducing muscle tissue temperature: a linear dose-response relationship. *J Sport Med Phys Fitness*. 2019;59(11):1861–1869.
13. Zhang H, Huizenga C, Arens E, Yu T. Considering individual physiological differences in a human thermal model. *J Therm Biol*. 2001;26(4–5):401–408.
14. Anderson GS. Human morphology and temperature regulation. *Int J Biometeorol*. 1999;43(3):99–109.
15. Toner MM, Sawka MN, Foley ME, Pandolf KB. Effects of body mass and morphology on thermal responses in water. *J Appl Physiol*. 1986;60(2):521–525.
16. Xu X, Castellani JW, Santee W, Kolka M. Thermal responses for men with different fat compositions during immersion in cold water at two depths: prediction versus observation. *Eur J Appl Physiol*. 2007;100(1):79–88.
17. Jackson AS, Pollock ML. Practical assessment of body composition. *Phys Sportsmed*. 1985;13(5):76–90.
18. Kirkendall DT, Grogan JW, Bowers RG. Field comparison of body composition techniques: hydrostatic weighing, skinfold thickness, and bioelectric impedance. *J Orthop Sports Phys Ther*. 1991;13(5):235–239.
19. Tothill P, Stewart AD. Estimation of thigh muscle and adipose tissue volume using magnetic resonance imaging and anthropometry. *J Sports Sci*. 2002;20(7):563–576.
20. Swain DP, Abernathy KS, Smith CS, Lee SJ, Bunn SA. Target heart rates for the development of cardiorespiratory fitness. *Med Sci Sports Exerc*. 1994;26(1):112–116.
21. Meeusen MP, Lievens P. The use of cryotherapy in sports injuries. *Sports Med*. 1986;3(6):398–414.
22. Glatting G, Kletting P, Reske SN, Hohl K, Ring C. Choosing the optimal fit function: comparison of the Akaike information criterion and the F-test. *Med Phys*. 2007;34(11):4285–4292.
23. Jutte LS, Hawkins J, Miller KC, Long BC, Knight KL. Skinfold thickness at 8 common cryotherapy sites in various athletic populations. *J Athl Train*. 2012;47(2):170–177.
24. Del Rosso S, Nakamura FY, Boullosa DA. Heart rate recovery after aerobic and anaerobic tests: is there an influence of anaerobic speed reserve? *J Sports Sci*. 2017;35(9):820–827.
25. Hellsten Y, Nyberg M. Cardiovascular adaptations to exercise training. *Compr Physiol*. 2011;6(1):1–32.
26. Schmidt W, Prommer N. Effects of various training modalities on blood volume. *Scand J Med Sci Sports*. 2008;18(Suppl 1):57–69.
27. Duz S, Kocak M, Korkusuz F. Evaluation of body composition using three different methods compared to dual-energy X-ray absorptiometry. *Eur J Sport Sci*. 2009;9(3):181–190.
28. Fanelli MT, Kuczmarski RJ. Ultrasound as an approach to assessing body composition. *Am J Clin Nutr*. 1984;39(5):703–709.
29. Orphanidou C, McCargar L, Birmingham CL, Mathieson J, Goldner E. Accuracy of subcutaneous fat measurement: comparison of skinfold calipers, ultrasound, and computed tomography. *J Am Diet Assoc*. 1994;94(8):855–858.
30. Sloan AW. Estimation of body fat in young men. *J Appl Physiol*. 1967;23(3):311–315.
31. Wagner DR. Ultrasound as a tool to assess body fat. *J Obes*. 2013;2013:280713.
32. Wagner DR, Cain DL, Clark NW. Validity and reliability of A-mode ultrasound for body composition assessment of NCAA Division I athletes. *PLoS One*. 2016;11(4):e0153146.
33. Gagge AP, Gonzalez RR. Mechanisms of heat exchange: biophysics and physiology. In: Fregley MJ, Blatteis CM, eds. *Handbook of Physiology: A Critical, Comprehensive Presentation of Physiological Knowledge and Concepts. Section 4, Environmental Physiology*. New York, NY: Oxford University Press; 1996:45–84.
34. Newton DJ, McLeod GA, Khan F, Belch JJ. Vasoactive characteristics of bupivacaine and levobupivacaine with and without adjuvant epinephrine in peripheral human skin. *Br J Anaesth*. 2005;94(5):662–667.
35. Xu X, Giesbrecht GG. A new look at survival times during cold water immersion. *J Therm Biol*. 2018;78:100–105.

Address correspondence to Talin Louder, PhD, Utah State University, 7000 Old Main Hill, Logan, UT 84322. Address email to talin.louder@usu.edu.